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14. ABSTRACT

Packing of granular media is an extremely important determinant in reservoir rock evolution, sound speed propagation, fluid flow and sediment compressibility. X-ray microfocus computed tomography (XMCT) images with high-resolution (~12 μm) were evaluated using a grain-based algorithm that quantifies discrete components (i.e.. pore/gram properties) and bulk properties (i.e.. permeability and grain interconnectivity) of sedimentary systems at different states of compaction or at approximately minimum and maximum packing densities Angularity of these sands ranges from rounded (i.e., ooids) to subrounded (i.e., accusands) to subangular (i.e., quartz sand from the beach). Network permeability compares reasonably well to measured values; grain aspect ratios and coordination number are reasonable for sands. The grain based algorithm provides a robust and efficient capability.

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computed tomography, permeability, aspect ratio, grain contacts

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Quantifying Consolidation and Reordering in Natural Granular Media from Computed Tomography Images

Allen H. Reed* — Karsten E. Thompson —Wenli Zhang**— Clinton S. Willson***—Kevin B. Briggs***

**Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS, 39529 USA*

allen.reed@nrlssc.navy.mil
kevin.briggs@nrlssc.navy.mil

*** Cain Department of Chemical Engineering, Louisiana State University, Baton Rouge, LA, 70803, USA*

karsten@lsu.edu
wzhang2@lsu.edu

**** Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA, 70803, USA*
cwillson@lsu.edu

ABSTRACT: *Packing of granular media is an extremely important determinant in reservoir rock evolution, sound speed propagation, fluid flow and sediment compressibility. X-ray microfocus computed tomography (XMCT) images with high-resolution (~12 μm) were evaluated using a grain-based algorithm that quantifies discrete components (i.e., pore/grain properties) and bulk properties (i.e., permeability and grain interconnectivity) of sedimentary systems at different states of compaction or at approximately minimum and maximum packing densities. Angularity of these sands ranges from rounded (i.e., ooids) to subrounded (i.e., accusands) to subangular (i.e., quartz sand from the beach). Network permeability compares reasonably well to measured values; grain aspect ratios and coordination number are reasonable for sands. The grain based algorithm provides a robust and efficient capability.*

KEY WORDS: *computed tomography, permeability, aspect ratio, grain contacts*

1. Introduction

Packing of granular media is an extremely important determinant in reservoir rock evolution, sound speed propagation, material strengths (*i.e.*, subsoil, beaches, and levees) and catalytic reactor efficiency. Although numerous packing simulations of simple systems (*e.g.*, spheres, cylinders, squares) have been conducted, the need to directly evaluate packing in real systems remains high. X-ray microfocus computed tomography (XMCT) imaging enables evaluations of complex processes in systems with complex geometries. Evaluation of these systems is often limited by a paucity of algorithms that effectively evaluate volumetric images and extract parameters that are necessary for modelling sound speed, material compressibility, or reactor processes; the algorithm (Thompson et al., 2006) that is applied to the sediments in this paper provides a means to evaluate trends and to quantify discrete and bulk pore/grain geometry from volumetric images; the need to disperse sediments to predict fluid properties and to determine grain geometry is eliminated. In this paper, we concern ourselves with further development and application of an algorithm, which has been applied to ideal particles (*e.g.*, spheres and cylinders) and manufactures sands (*i.e.*, accusands) to naturally occurring sands which have increasingly complex geometries and which are packed to different densities (Thompson *et al.*, 2006). The sand samples are ooids, an authigenic calcareous sediment, accusands, which are manufactured from rock and size-sorted, and quartz sand from the Northern Gulf of Mexico (NGOM) adjacent to western Florida; these sands are referred to as ooids, accusands and NGOM. The sand samples are packed to different densities that simulate natural ranges of sediment packing and, thus, the algorithm enable us to study the effects of consolidation on sediment properties at the pore scale (*e.g.*, permeability, grain coordination number).

2. Methods

High-resolution XMCT images (11.75 micrometer voxels) of sands were collected using an industrial computed tomography scanner in 8-mm diameter columns that were packed to approximate minimum and maximum density. After the minimum-density sample is scanned, the sand is consolidated by tapping and vibrating the column to achieve a maximum-density packing. Then the sample at maximum-density packing was scanned to capture the influence of the new packing order. Volume image files were corrected for beam hardening (*i.e.*, differential attenuation of x-rays within a sample that occurs in polychromatic CT systems; *see* Wellington and Vinegar, 1989), converted to cubic voxels and segmented into pores and grains using an indicator kriging algorithm (Oh and Lindquist, 1996; [Figure 1]). Within these volume files, individual pores and grains are discretized using a grain based algorithm (Thompson *et al.*, 2006), which is summarized by the following steps: a signed distance map $d(i,j,k)$ is created within the voxel array

(denoted by voxel positions *i,j,k*), and maxima in the function are used to identify potential grain locations. The locations of grain centers are refined using a non-linear optimization, and the grains are uniquely identified using a restricted burn procedure (Figure 2). The final grain-phase map labels each voxel with the grain number to which it belongs. Statistics on sizes and distributions, connectivity and contact area (grains) are then determined. Because the automated grain-reconstruction process can fail for odd-shaped grains, parameters such as grain aspect ratios and grain coordination number (*i.e.*, number of grain contacts per grain) are used to identify select grains, which are isolate from the volume and examined individually to determine if single grains were broken into multiple pieces and need to be combined or whether grains were joined and need to be subdivided (Figure 3).

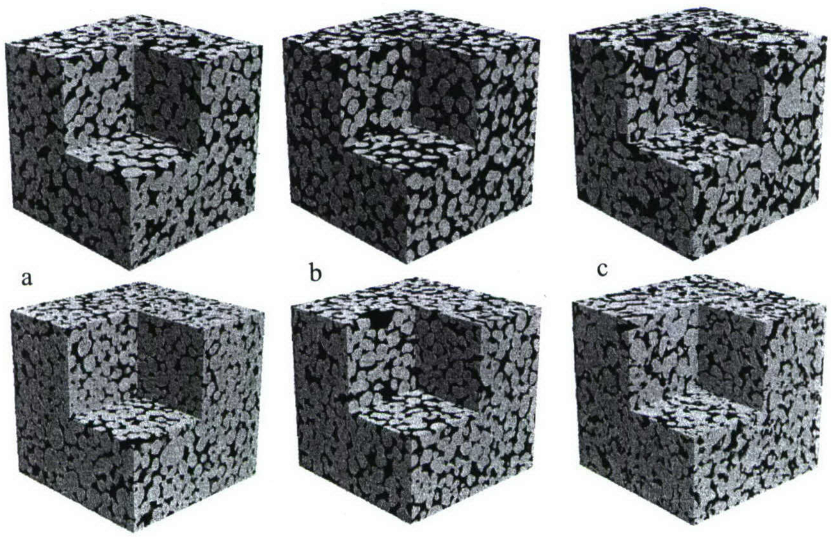

Figure 1. *Ooid sand (a), accusands (b) and NGOM sand (c) were packed from a near minimum- (top) to near maximum-density packing (bottom). The dark gray in these segmented or 1-bit binary images represents pore space, which is reduced in the bottom row, and the light gray represents grains. Samples are 350 voxels (4113.2 μm) in each dimension*

Using the grain locations as a template, pore throats and pore bodies are separated as in a pore-network. This is analogous to an electrical network where the pore throats are the bonds through which water is conducted and the pore bodies are the nodes into which water is directed to the connecting pore throats. Once the pore-

network is created for the sample, it can be used for sample characterizations well as flow simulation and permeability predictions (Thompson *et al.*, 2005).

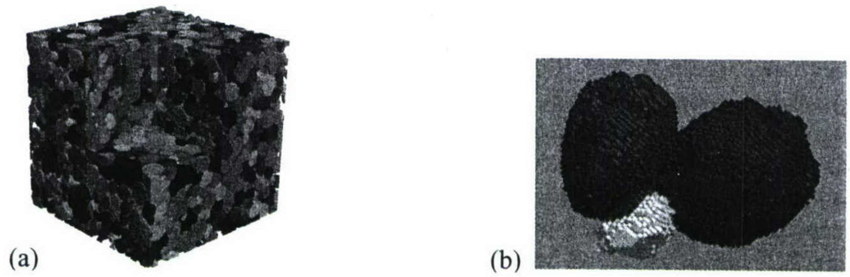

Figure 2. *An example of the sand evaluation with from ooids that were packed to a minimum density packing (a). The different grayscales are used to differentiate grains, not to categorize them. Grains are evaluated as discrete particles as in the case of the three ooid grains (b), which were extracted from the larger volume (a)*

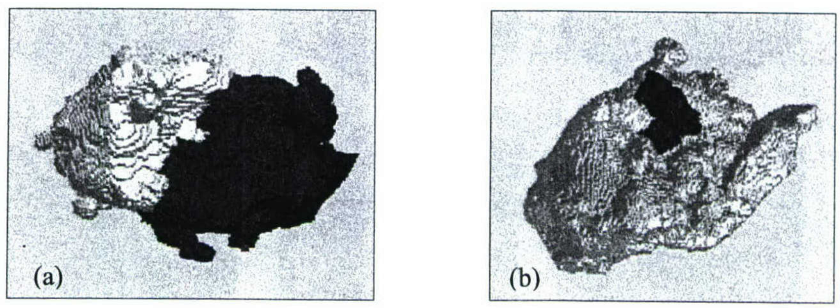

Figure 3. *A single angular quartz grain is depicted as two separate grains (a), which are differentiated by grayscale. The two large "grains" fit the criterion of large contact surface area to grain size, so the grains are merged together. Small grains (dark gray) with proportionally large contact areas to grain size are set to merge automatically (b)*

3. Results

The network models for these sediment packings were used to determine permeability values (Figure 4). These values are slightly higher than bulk permeability values (2.50×10^{-11} m^2), which were determined using a constant-head permeameter on 13-cm long, 6-cm diameter cores of naturally deposited NGOM sands, which were carefully collected from the seafloor by SCUBA divers.

Grain aspect ratios and coordination numbers increase as sediment angularity increases (Figure 5). The grain contact area determined from these images is skewed, in a limited number of cases, due to the shape of the grains prior to subdividing or merging (Figure 2). Once the grains are merged, the aspect ratios and trends in coordination numbers for variably shaped grains packed to different densities are represented accurately. Predictions of grain coordination numbers can benefit from further refinement of the algorithm.

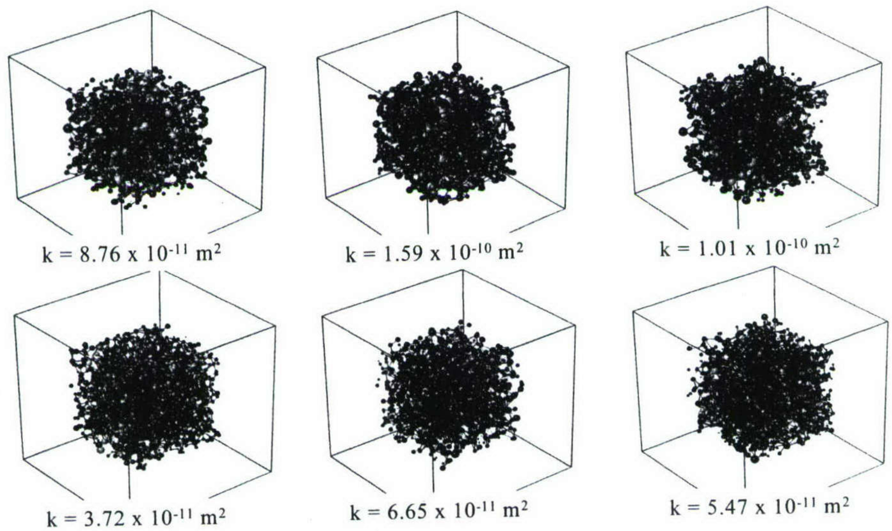

Figure 4. *Pore networks, used to determine permeability, are represented with ball-stick (pore body-pore throat) geometric configurations. Permeability values are presented for ooid sands (left column), accusands (center column) and NGOM sands (right column) below the respective sample for low-density (top row) and high-density (bottom row) packings*

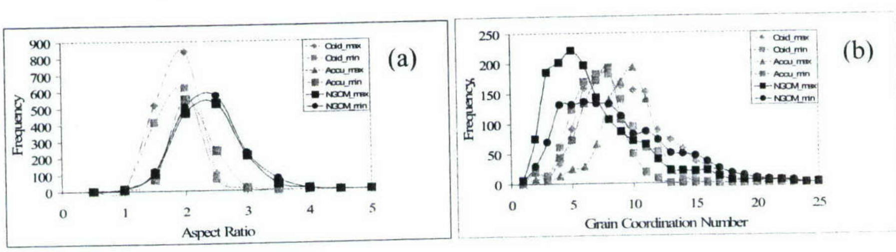

Figure 5. *Aspect ratios (a) and coordination numbers (b) for the ooid sands (Ooid), accusands (Accu) and NGOM sands (NGOM) at the minimum-density (min) and maximum-density (max) packings. Coordination numbers increasing with increased density indicated an increased rigidity and shear modulus*

4. Discussion and Summary

A grain based algorithm that was previously developed for analysis of granular media (Thompson et al., 2006) has been applied to naturally occurring sands that have shapes ranging from rounded (*i.e.*, ooids) to subrounded (*i.e.*, accusands) to subangular (*i.e.*, NGOM sand). This algorithm provides a marked improvement in our ability to assess sand shape and sediment fabric in sands, because grains can be evaluated in relationship to other grains, within a sediment volume, and without grain dispersal. This algorithm provides both pore statistical information, which can be readily employed to evaluate the flow properties of the sand, and grain statistic information, which can be used to evaluate individual grain shapes within a sediment volume. Additionally, the relationship of each grain to its neighbour is evaluated and trends related to sediment consolidation, such as grain coordination numbers (grain-connectivity) can be obtained.. Future work will address grain contact information more fully by making further refinements to the algorithm, so that we can determine whether grain contact relationships may be used to effectively predict sediment rigidity and sediment compressibility, that is shear and bulk moduli.

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Advances in X-ray Tomography for Geomaterials

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ISTE

Originally developed for use in healthcare, X-ray computed tomography has been increasingly used in the field of non-destructive material testing. Computed tomography (CT) is useful for studying a wide range of materials, for example, rock, bone, ceramic, metal and soft tissue. Recently, the study of geomaterials (including granulates, soils, rocks and concrete) has become one of the more active and challenging fields for the application of high-resolution X-ray CT.

This book brings together a total of 48 contributions (including 5 keynote papers) which were presented at the 2nd International Workshop on the Application of X-ray CT for Geomaterials (GeoX 2006) held in Aussois (France) on October 4-7, 2006. The contributions cover a wide range of topics, from fundamental characterization of material behavior to applications in geotechnical and geoenvironmental engineering. Recent advances of X-ray technology, hardware and software are also discussed. As such, this will be valuable reading for anyone interested in the application of X-ray CT to geomaterials from both fundamental and applied perspectives.

Jacques Desrues is Research Professor in Laboratoire 3S at CNRS, Grenoble, France. He has been a member of CoNRS (the French Evaluation Committee of Scientific Research) since 2000 and his research interests include Deformation and Failure in Geomaterials, Experiments and Modeling.

Gioacchino (Cino) Viggiani is Full Professor of Civil Engineering at Université Joseph Fourier, Grenoble, France. His research interests include Strain Localization and Constitutive Modeling.

Pierre Bésuelle has been Research Associate Professor at CNRS, Grenoble, France since 2001. His research interests include Homogenous and Localized Deformation in Rocks, Advanced Testing and Models.

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